

Scientific paper

Studies on climatic and environmental changes during the last few hundred years using ice cores from various sites in Nordaustlandet, Svalbard

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Abstract: Ice coring and snow cover observations have been carried out at 3 sites in Nordaustlandet, Svalbard since 1995. The results of stratigraphic analyses, and chemical and $\delta^{18}\text{O}$ analyses from Vestfonna and Austfonna cores are presented here. The results from these sites show that most of the chemical constituents contained in the initial snow cover still remained in the ice cores, although re-distribution of them by melt water percolation had occurred. Anthropogenic increases in trace metals, sulfate and nitrate since about 1950 are detected. This suggests that ice-core chemistry records from Nordaustlandet, Svalbard, can be useful to reconstruct past atmospheric conditions. In addition to chemical records, $\delta^{18}\text{O}$ records, that correlate well with the temperature records in Svalbard, can be used to reconstruct past temperature changes.

1. Introduction

The Arctic region is a heat sink in the global climate system and acts as a convergent region of substances that are released into the atmosphere from various sources. It is believed that the types and amounts of substances vary with climatic and/or environmental fluctuations, so the state of these substances in the atmosphere in the Arctic can be considered as a kind of signal indicating what the climate and environment is like. Such substances, transported in the atmosphere over polar ice sheet or glacier, are eliminated by wash-out and dry fall-out processes from the atmosphere onto the snow surface. They become mixed into and then are fixed into the snow and ice structure.

The cryosphere covers over the Arctic. Its fluctuation affects or is affected by the global climate system. Svalbard is one of the most northern islands, where the fluctuation of the glacier system possibly affects and/or is affected by the Arctic climate. Svalbard is located in the European sector of the Arctic, where artificial activities have historically been active. Snow chemistry has been affected by human activities.

Ice coring and snow observations have been carried out at 3 sites in Nordaustlandet, Svalbard since 1995. The purposes of this research project are as follows: (1) to understand regional characteristics of post-depositional changes under present climatic conditions, and

(2) to reconstruct climatic and environmental changes in Svalbard during the last few hundred years (Watanabe, 1996). Topic (1) is necessary for the investigation on temperate glacier and (2) valid under the topics (1).

Since most of the glaciers in Svalbard suffer rather severe melting even in their highest parts (*e.g.* Hagen and Liestøl, 1990), ice-core investigations have not been paid enough attention. Interpretation of ice-core records from areas of high melt has often been misleading (Koerner, 1997), even if ice-core data exist. However, ice caps or glaciers with relatively heavy melt can still provide us with important climatic and environmental information, if the data are properly interpreted. Most of the sites studied in this research

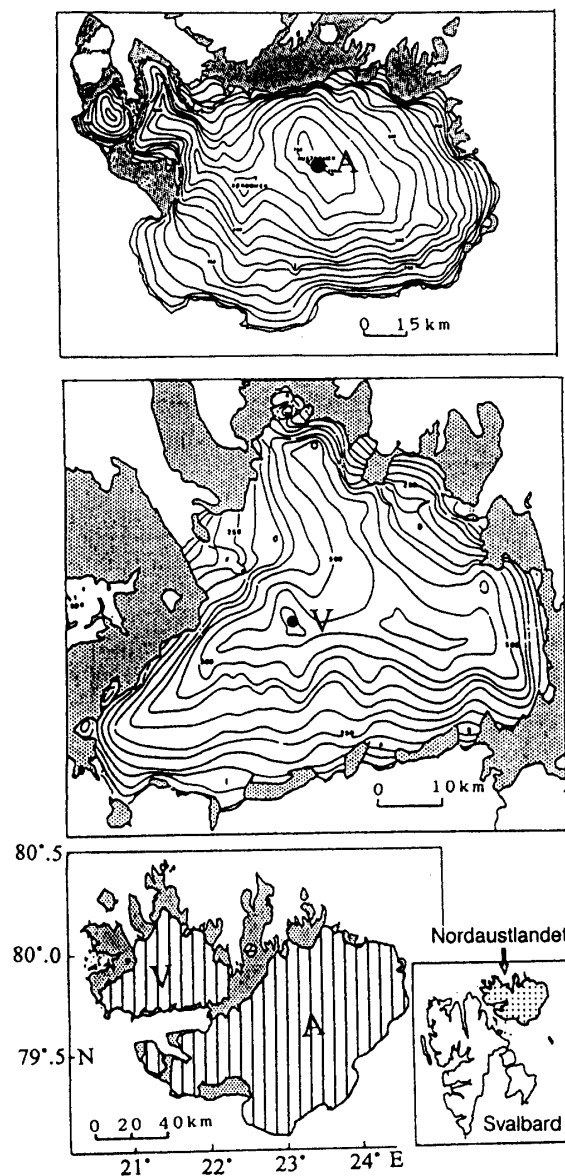


Fig. 1. Locations of drilling sites in Nordaustlandet, Svalbard.
V: Vestfonna, A: Austfonna, ●: Drilling site.

project were located in the “percolation zone” and “dry snow zone”, and melt water infiltration-refreezing conditions were different between the sites.

2. Ice coring in Nordaustlandet

2.1. Locations of ice coring site and glaciological condition

An ice core, reaching to the bottom of Austfonna glacier, was previously obtained by a Russian team (Arkhipov *et al.*, 1987); however, detailed analytical results of the core have not yet been published.

Glaciological conditions of the site above are as follows: ice thickness is 560–580 m

Table 1. Ice coring sites in Svalbard.

Drilling sites	Drilling date	Location	Altitude (m a.s.l.)	Drilling depth (m)	10 m ice temp. (°C)	Average density ($\text{kg}\cdot\text{m}^{-3}$)		Reference
						0–10 (m)	10–20 (m)	
Vestfonna	May–Jun. 1995	79°58'N, 21°01'E	600	210.0	−3.7	639	839	This study
Austfonna	Mar.–Apr. 1998	79°48'N, 24°00'E	750	118.6	−1.0	601	876	This study
Austfonna	Apr.–May 1999	79°50'N, 24°01'E	750	289.1	−2.8	649	840	This study
Høghetta Ice Cap	May–Jun. 1987	79°17'N, 16°50'E	1200	85.6	−11.0	(ice)	(ice)	Fujii (1990)
Snøfjellaonna	Jul.–Aug. 1992	79°08'N, 13°18'E	1190	83.9	−2.8	565	775	Kameda (1992)
Åsgårdfonna	Jun.–Jul. 1993	79°27'N, 16°43'E	1140	185.3	−6.8	808	881	Uchida (1996)

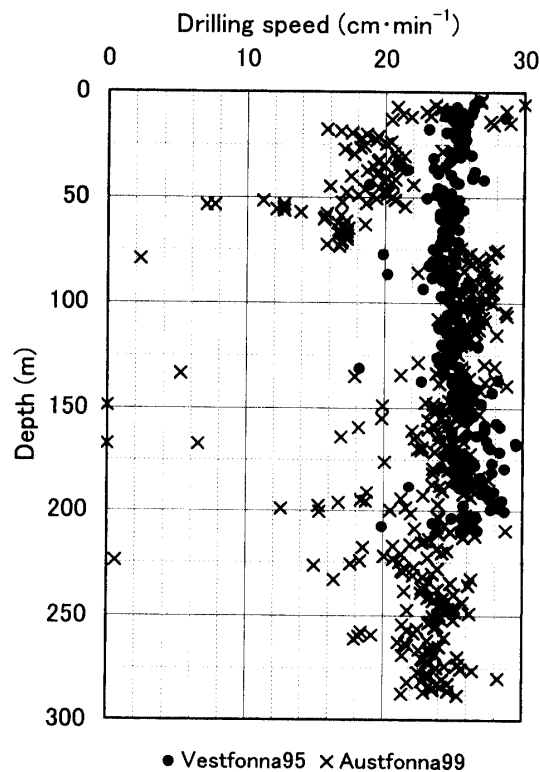


Fig. 2. Drill speeds at Vestfonna, and Austfonna drilling.

(Arkhipov *et al.*, 1987), annual accumulation rate is $0.5\text{--}0.6\text{ m}\cdot\text{yr}^{-1}$ in water eq. (Sinkevich and Tarusov, 1989), and 10 m snow temperature is -4°C (Zagorodonov and Arkhipov, 1990).

These are two glaciers in Nordaustlandet; Austfonna glacier and Vestfonna glacier. North Dome (Norddomen) of Austfonna glacier and the summit of Vestfonna glacier were selected as the representative ice coring sites (Fig. 1). Geographical and glaciological conditions are described in Table 1.

2.2. Coring operation

All the drilling operations were carried out in spring. All of the ice cores listed in Table 1 were excavated with electromechanical drills. The cores were drilled with the same electromechanical drill (Takahashi, 1996), whose length was 3.0 m. Diameters of the core and the bore hole were 94 mm and 129 mm, respectively.

Average drilling speeds at Vestfonna and Austfonna were 26.2 cm/min and 17.0 cm/min, respectively. Drilling speeds are plotted against depth in Fig. 2. Variations in drilling speed reflect variations in the physical properties of firn and ice. In general, ice (firn) becomes harder with decrease in ice (firn) temperature and also with increase in ice (firn) density, and thus drilling speed decreases. The greater drill speeds resulted from the much higher ice (firn) temperatures and thus the softer nature of ice (firn). At depths greater than 120–130 m, ice tends to break into pieces. At these depths, the ice core was fragile and easily broke, reflecting the change in physical properties of ice at 120–130 m depth. Although the drilling can take a 0.7–0.9 m long core in one drilling run, the ice layer may originally have fractures. The core obtained below 250 m in depth turned out to be in more stable condition.

3. Analytical results

3.1. Surface layer stratigraphy

Surface snow stratigraphical observations and snow sampling were carried out at snow pits near the three drilling sites. Due to irregularity of snow cover characteristics caused by selective melt water infiltration relating to the surface topography, pit observations were made at 3–5 locations around each drilling site. Snow cover stratigraphy provides information on the annual accumulation rate at the drilling sites, behavior of melt-water movement, formation mechanism of superimposed ice and other depositional phenomena.

The vertical distributions of stratigraphy, snow density, oxygen isotopic composition and chemical constituents are shown in Fig. 3. As is obvious from these profiles, the uppermost layer still retains its original condition during snow deposition. But homogenization by melt water infiltration occurred in the layer below 100–150 cm from the surface, taking the profiles into consideration.

From these data, these areas are judged to be in a “percolation zone”. Annual layer boundaries can be recognized by the development of granular snow layers and dirt surface structures. In the surface snow cover in Vestfonna and Austfonna of 1995 and 1999 drilling sites, the uppermost annual layer was composed of 5–6 unit layers. Here a unit layers results from continuous deposition during a snowfall season. In these profiles of $\delta^{18}\text{O}$ and ion concentrations, two or three peaks in the annual layer exist. These phenomena may reflect

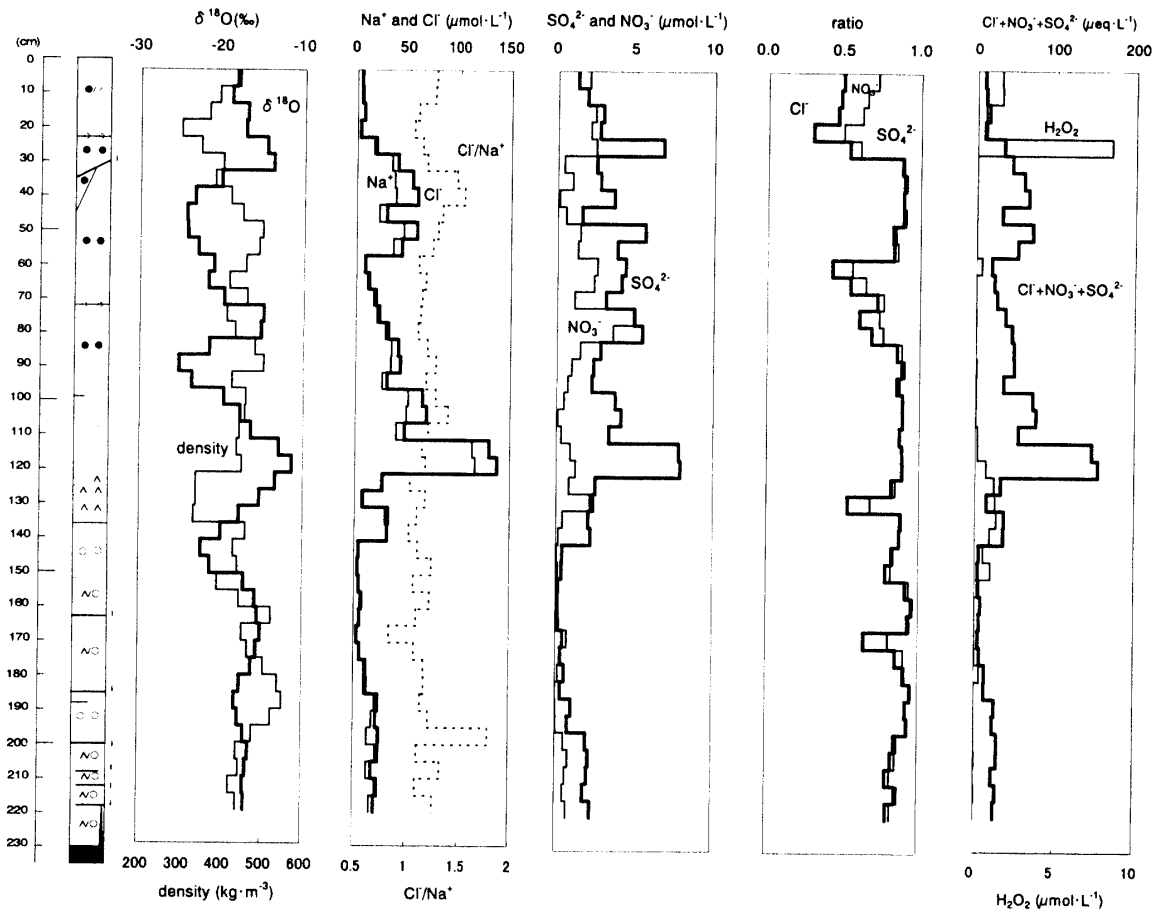
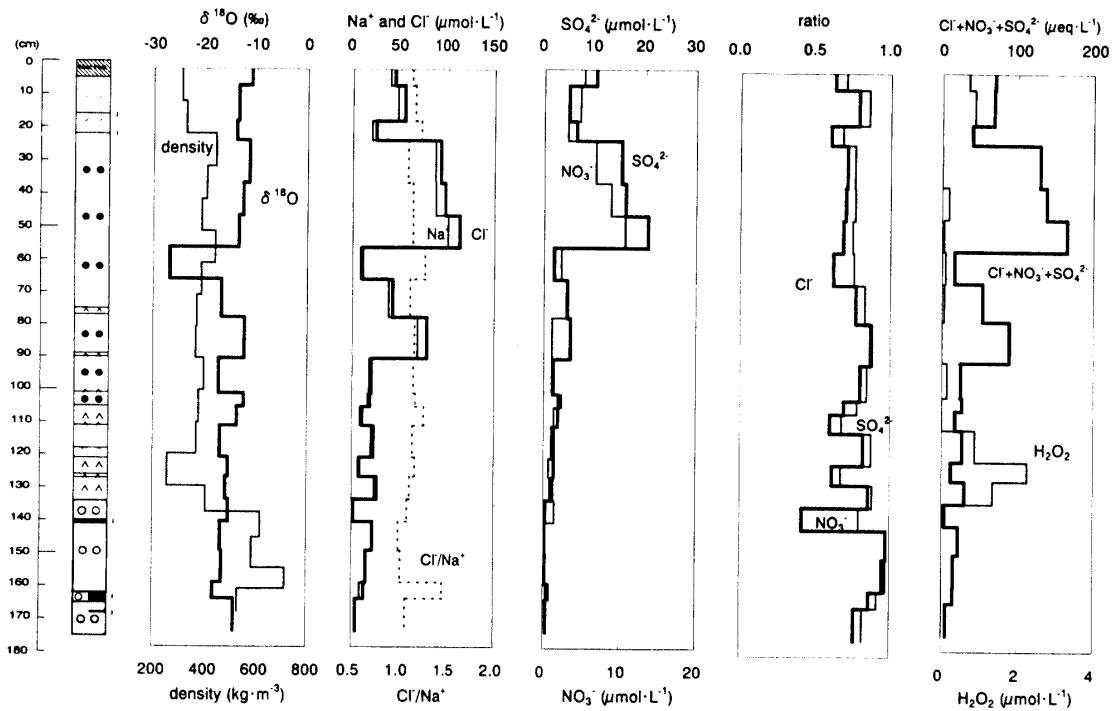
Vestfonna 1995**Austfonna 1999**

Fig. 3. Stratigraphic diagram of the surface snow cover at Vestfonna drilling site and Austfonna drilling site. Snow texture: solid circle (granular snow), Δ (depth hoar).

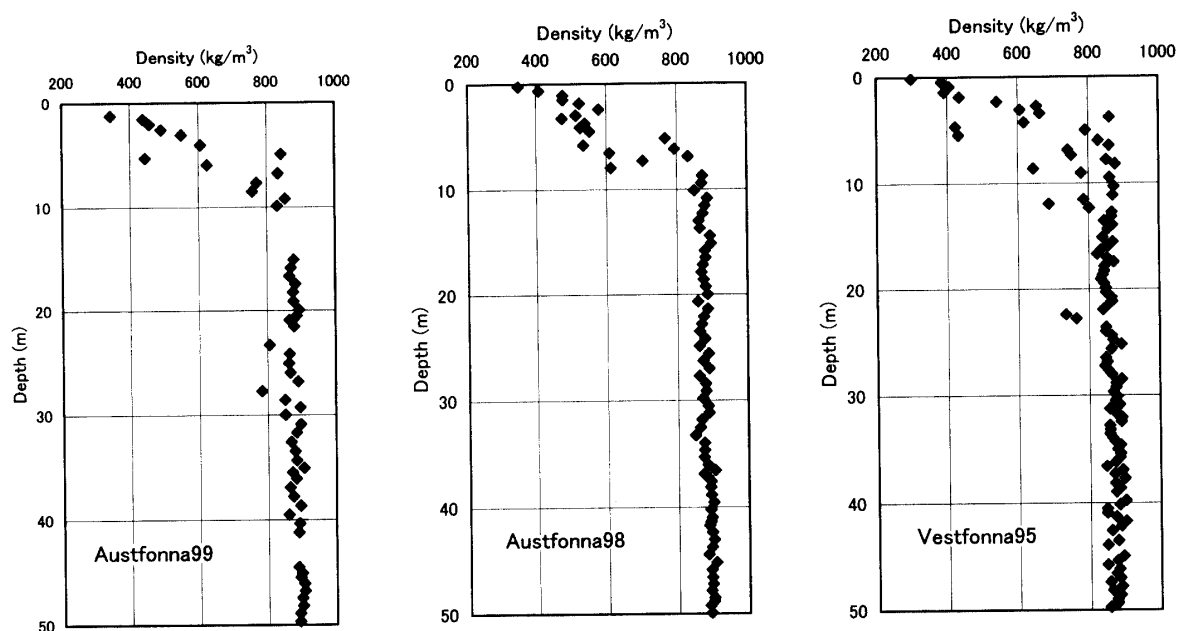


Fig. 4. Density-depth profiles at Vestfonna, and Austfonna coring.

meteorological conditions rather than seasonal variation (Motoyama *et al.*, 2001).

3.2. Physical properties

The density-depth profiles at three drilling sites in Vestfonna and Austfonna are shown in Fig. 4. The weights and diameters of the ice core were measured, *in situ*, at the site for the determination of density. As shown in this figure, change from firn to ice occurred in the 5–12 m depth range. Figure 4 suggests that melt water percolation played a major role in the firn/ice transition.

The borehole temperatures are shown in Fig. 5. Comparing these temperature profiles in the depth range of 0–80 m, it was considered that the drilling site on Austfonna was the coldest one. The temperature profiles in these 3 sites show similar tendencies in the depth range of 30–80 m, while the shallower parts look somewhat different. The temperature profiles of Høghetta, Åsgårdfonna and Snøfjellafonna, located on Spitsbergen, are shown for reference. These glaciers are all affected by melt water percolation. The behavior of melt water affected the temperature profiles near the surface.

3.3. Firn ratio measurements

Each ice core was divided into three parts (A: 60%, B: 25%, C: 15% in the horizontal section) vertically and the visible stratigraphy was observed *in situ*. The cores consisted of ice and firn; firn layers were dominant, especially in the upper part. The firn ratio means firn portion of a unit length of vertical section of a core.

Firn ratio profiles of 1995 and 1999 cores are shown in Fig. 6. The solid profiles are running means of 5 points at 2 m intervals (1995 core) and 7 points at 1 m intervals (1998 and 1999 cores).

There are two processes in ice formation. One is refreezing of surface melt water

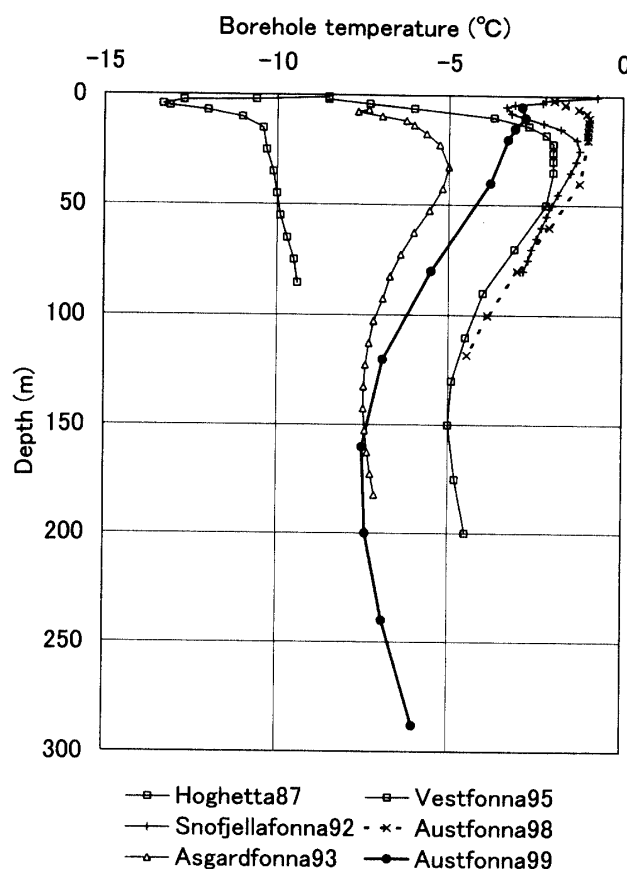


Fig. 5. Borehole temperature profiles at Vestfonna, Austfonna, Høghetta Ice Dome, Snøfjellaafonna and Åsgårdfonna.

percolation to the lower firn layer; the other is compression of the firn layer by the weight of the upper layer. The latter process accelerates at higher snow temperature and/or with water soaking. This process has a close relationship with the ice temperature as shown in Fig. 5.

3.4. ECM measurements

For detection of acid layers and/or signals which originated from volcanic activities, ECM measurements are useful and were performed in situ. Some of the high ECM signals in the Arctic core correspond to those of large volcanic eruptions, such as Katmai 1912, Tambora 1815, Laki 1783 and so on (Table 2).

The ECM signal is the intensity of electric current between electrodes. After shaving about 1 cm off the cutting surface of the A part (60% in areal portion of core), ECM measurements were made vertically, with electrodes in direct contact with the ice surface. As seen in Fig. 7, several volcanic signals are extracted from the ECM measurements. Marked signals that originated from Icelandic Laki volcanic activity in 1783 were found at a depth of 106.23 m in the 1999 core.

In this figure, tritium concentration (TU) is added. The reference horizon of the 1963 radioactivity peak derived from a nuclear bomb test is found at a depth of 21.11–54 m in

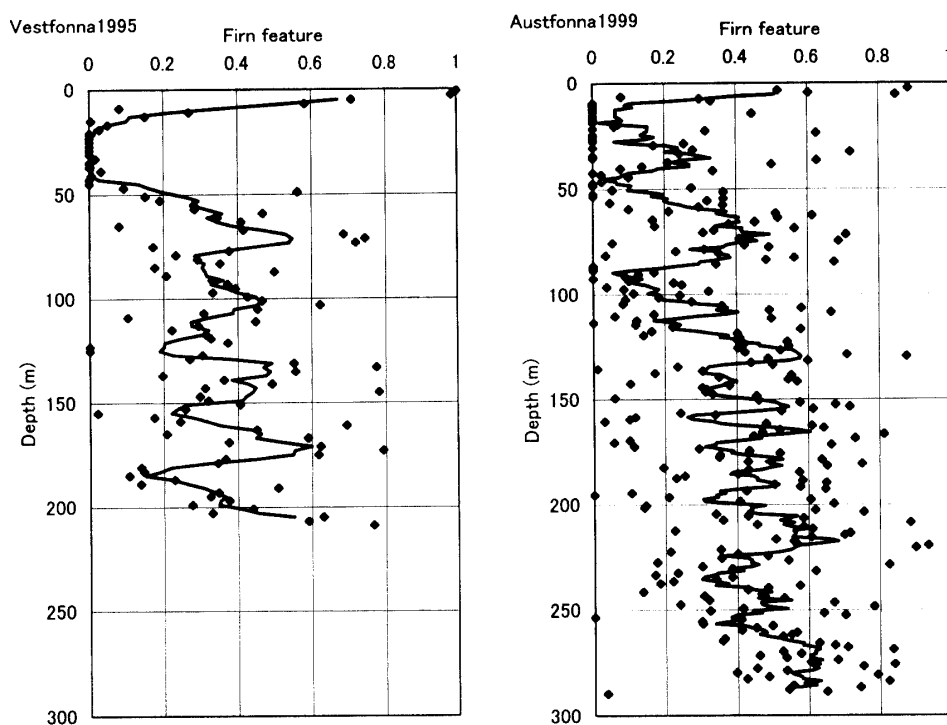


Fig. 6. Vertical profile of the firn ratio on Vestfonna core and Austfonna core.

Table 2. List of various events detected from Austfonna 1999 core.

Event	Year	Evidence	1999 Austfonna Core		Acc. rate (m-water·a ⁻¹)	Interval
			Depth (m)	Depth (m. w.eq)		
Hekla	1970	ECM peak	18.0	13.4		
Nuclear test (A)	1963	Tritium peak	21.3	16.3	0.45	Drilling-1963
$\delta^{18}\text{O}$ rise (B)	1920's	$\delta^{18}\text{O}$ profile	49.0	40.6	0.57	1963-1920
Katmai	1912(?)	ECM peak	52.2	43.5		
Santa Maria	1902(?)					
Tambora	1815(?)	ECM peak	96.4	83.3	0.48	1912 or 1902
Unknown	1809(?)					1815
Laki (C)	1783	ECM peak	106.6	92.9	0.32	1815-1783
Oræfajökull	1727	ECM peak	128.5	112.3	0.38	1783-1727
St. Helens (D)	1482(?)	ECM peak	220.3	195.1?	0.38	1783-1482
Berdarbunga (D)	1480(?)					or 1480

the 1999 core. Laki signals, detected by ECM measurements, were also detected at 86 m (73.3 m-water equivalent) in the 1995 core and 15.3 m in the 1995 core, and tritium debris at 20.96 m in the 1998 core (Kameda *et al.*, 1993; Pinglot *et al.*, 1994).

3.5. Oxygen isotopic composition

Continuous oxygen isotopic composition measurements were made by MAT delta-E mass spectrometer along the whole depth of cores drilled in Nordaustlandet. The sample size corresponds to the estimated annual layer thickness. Results are shown in Fig. 8 together with those of Åsgårdfonna, and air temperature data observed at Isfjord Radio.

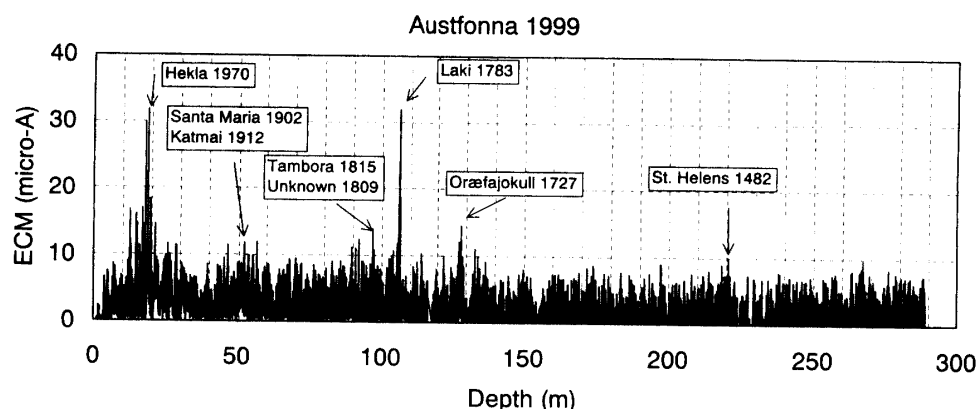


Fig. 7. ECM profile on Austfonna core. Thin arrow: Detected volcanic activity layer.

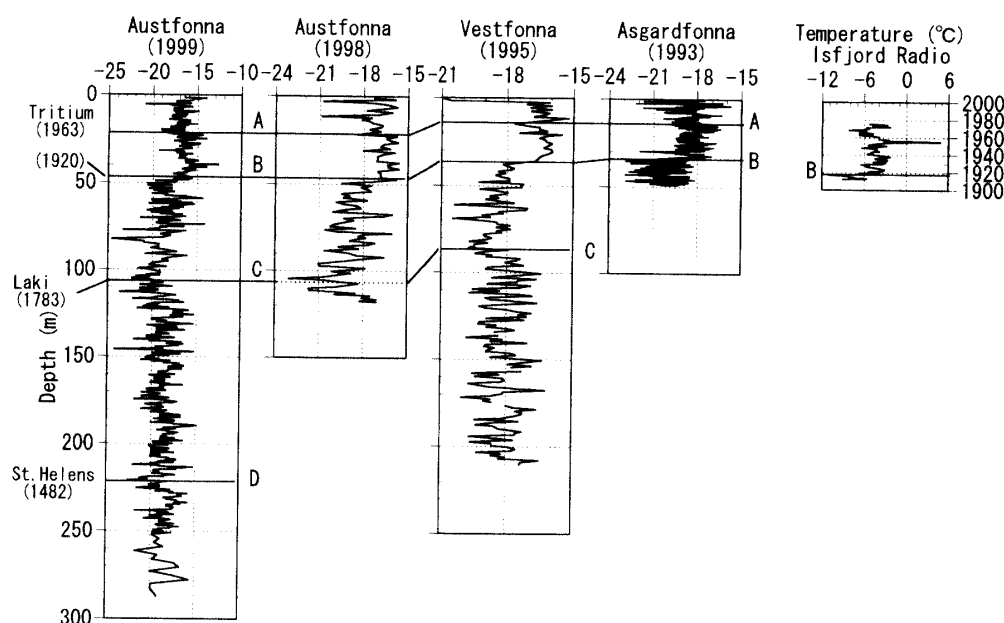


Fig. 8. Comparison of stable oxygen isotope profiles in Nordaustlandet core. Letters are reference horizons indicated by various events.

As seen in Fig. 8, oxygen profiles indicate the common tendency of climate change. Abrupt rise of temperature (or of $\delta^{18}\text{O}$) occurred at depths of 45 m in the Austfonna 1998 and 1999 cores and 35 m in the Vestfonna 1995 core. This abrupt rise of temperature may correspond to the temperature rise which occurred at the beginning of the 1920's, observed at Isfjord Radio meteorological station, which also corresponds to the general climatic tendency of the last century in the northern hemisphere (Hanssen-Bauer *et al.*, 1990).

3.6. Chemical constituents

The vertical concentration profiles for the cations Na^+ and Ca^{2+} and the anions SO_4^{2-} and NO_3^- , in the Austfonna 1999 core, are shown in Fig. 9. There is no obvious trend

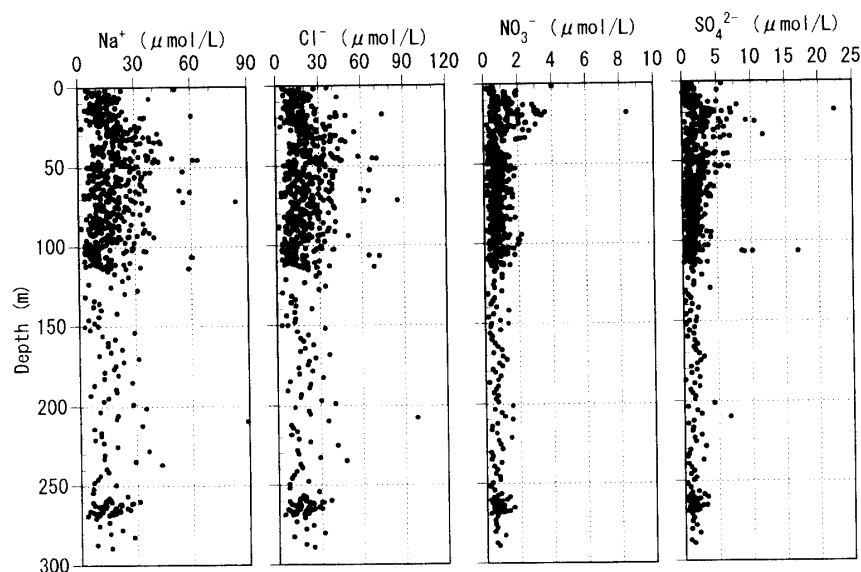


Fig. 9. Vertical profiles of chemical composition in Nordaustlandet cores.

Table 3. Average of annual chemical flux in the specific interval defined by the events.

1) Vestfonna 1995 Ice core											
Interval (year)	Depth (m)	Concentration					Acc. rate (m·water·a ⁻¹)	Flux			
		Na ⁺	Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺		Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	
		(μ mol·L ⁻¹)				(m mol·m ⁻² ·a ⁻¹)					
1963–1995	0–	15.3	25.52	1.47	1.58	3.31	0.34	8.68	0.50	0.54	1.12
1920–1963	15.3–	36.9	24.92	0.91	0.70	2.32	0.43	10.71	0.39	0.30	1.00
1783–1920	36.9–	86.0	27.48	1.35	0.87	2.45	0.35	9.62	0.47	0.31	0.86
–1783	86.0–211		29.01	1.04	0.53	1.57					
2) Austfonna 1998 Ice core											
Interval (year)	Depth (m)	Concentration					Acc. rate (m·water·a ⁻¹)	Flux			
		Na ⁺	Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺		Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	
		(μ mol·L ⁻¹)				(m mol·m ⁻² ·a ⁻¹)					
1963–1995	0–	20.9	15.88	0.73	1.54	1.88	0.45	7.15	0.33	0.69	0.85
1920–1963	20.9–	48.0	22.81	0.65	0.59	1.15	0.58	13.23	0.37	0.35	0.67
1783–1920	47.5–	106.0	14.81	0.57	0.55	0.81	0.41	6.07	0.23	0.22	0.33
–1783	106.0–118.5		12.54	0.50	0.41	0.53					
3) Austfonna 1999 Ice core											
Interval (year)	Depth (m)	Concentration					Acc. rate (m·water·a ⁻¹)	Flux			
		Na ⁺	Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺		Ca ²⁺	NO ₃ ⁻	SO ₄ ²⁻	
		(μ mol·L ⁻¹)				(m mol·m ⁻² ·a ⁻¹)					
1963–1995	0–	21.3	14.57	0.53	1.32	2.06	0.45	6.55	0.24	0.60	0.93
1920–1963	21.3–	49.0	22.01	0.64	0.86	2.45	0.57	12.55	0.37	0.49	1.40
1783–1920	49.0–	106.6	17.27	0.76	0.80	1.78	0.44	7.60	0.34	0.35	0.78
–1783	106.6–289		15.79	0.62	0.64	1.32					

reflecting climatic or environmental variability. SO_4^{2-} and NO_3^- concentrations increase in the recently deposited layer, at a depth of about 10 to 20 m, indicating recent acidification. The marked peak in SO_4^{2-} and acidity around 105 m in the 1999 core is believed to be due to the eruption of Laki in 1783.

Annual fluxes of ions at each site were estimated by multiplying mean ion concentrations by annual mean accumulation rates. Mean annual fluxes of several ions were calculated over the intervals between the reference horizons (marked with letters in Fig. 8). Horizon A is detected by the tritium peak, B by a sudden decrease of oxygen isotopic ratio, and C by the estimation for ECM measurement of Laki.

Table 3 lists the averaged concentrations of ions; annual mean fluxes of ions, and annual mean accumulation rates at these sites.

4. Ice-core dating

Ice-core dating with high resolution by annual layer counting was not possible, since snow melting and melt water percolation disturbed the seasonal variation of ions and $\delta^{18}\text{O}$. For the preliminary estimation, the 1999 core was dated by means of Nye's time scale assuming a constant accumulation rate. In applying Nye's time scale, if the glacier thickness (H^*) is taken to be 654 m (corresponding to 600 m in water), the age (t) of ice at depth Z as a function of the accumulation rate A at the glacier surface is given by the following formula:

$$t = (\text{drilling year}) - H^* (\ln (H/(H - Z)))/A.$$

The average accumulation rates in the 1999 core between numbers of reference horizons are given in Table 2. First, to find a tentative "working" age, the average accumulation rate between 1999, the year of drilling, and 1963, the year of a nuclear test indicated by a local peak of tritium content, was found. In this way the average annual accumulation rate was found to be 507 mm of ice, equivalent to 465 mm of water.

The age given by the depth-year relationship was compared with the evidence of volcanic signals found by ECM as a check on accuracy; the difference between the two methods was within a few years in the upper layers. The older the age, the harder it becomes to identify the volcanic eruption responsible for a certain signal, but even so, the difference was less than about 10 years.

5. Reconstruction of the past environment and climate

It is well known that the oxygen and hydrogen isotopic composition ($\delta^{18}\text{O}$ and δD value) profiles are indicators of air temperature variability. The relationship between the stable isotope composition of water and air temperature on Nordaustlandet precipitation has not been clarified until now, because there occurred much local variation. However, relative fluctuation of air temperature can be determined.

In order to reconstruct climate change in Nordaustlandet, deviations from the average isotopic composition level, 50 years averages of isotopic composition were calculated. The relationship between the core age and $\delta^{18}\text{O}$ profile (indicating raw and running mean data) is shown in Fig. 10.

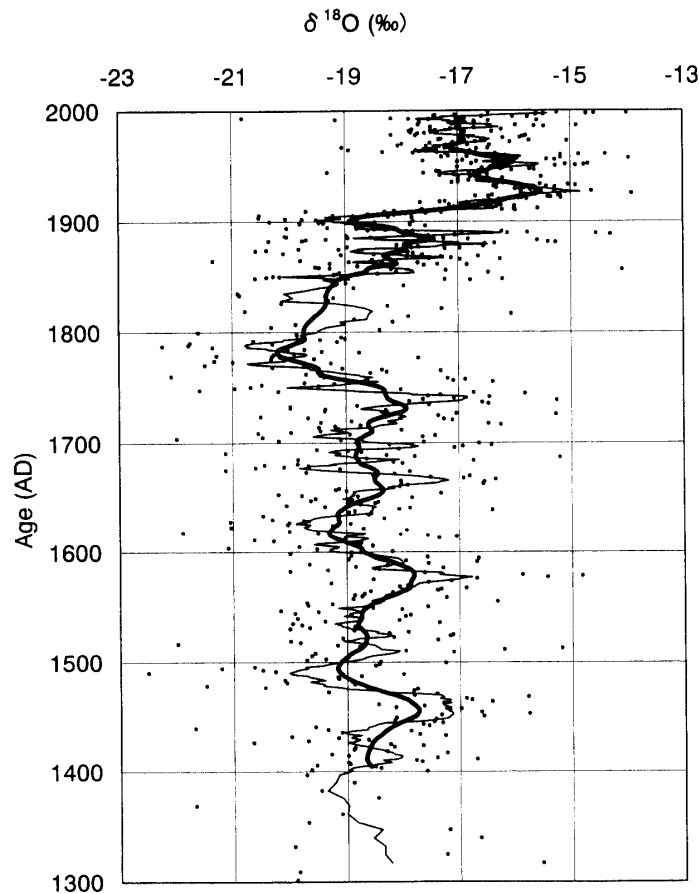


Fig. 10. Oxygen isotope profile on the estimated core age axis.

Inter-annual variability of oxygen isotope composition is shown as 50-year running means in Fig. 11. Open circles in the figure are 50-year means of isotope composition. The overall average from 1400 to 1900 is -18.7‰ ; since 1900, when air temperature has been rising rapidly, the average is -16.7‰ .

The air temperature variability trend shown in the 1999 core shows that the most recent colder period, "Little Ice Age" (or Neoglaciacion IV), ended around 1910, followed by a warming trend after about 1920. The difference of oxygen isotope composition between the Little Ice Age and the 20th century is about -2‰ .

Before 1920, during the Little Ice Age, there were also prominent cool trends; from 1475 to 1550 (C1), from 1600 to 1650 (C2), from 1680 to 1720 (C3) and from 1750 to 1860 (C4). These decades do not exactly agree with the cooler periods in Europe during the Little Ice Ages found by Schove (1961); 1541–1680, 1741–1770 and 1801–1890, with overlap duration.

The 1750–1860 cold period (C4) is believed to correspond to the pronounced 1835–1870 cold period found at Site J on the Greenland Ice Sheet (Kameda *et al.*, 1995), but the cold period lasted longer in Nordaustlandet and the cooling, recorded by the difference in oxygen isotopic ratio, was stronger. The air temperature variability trend also shows general agreement with that in the Greenland Dye 3 core (Dansgaard *et al.*, 1975).

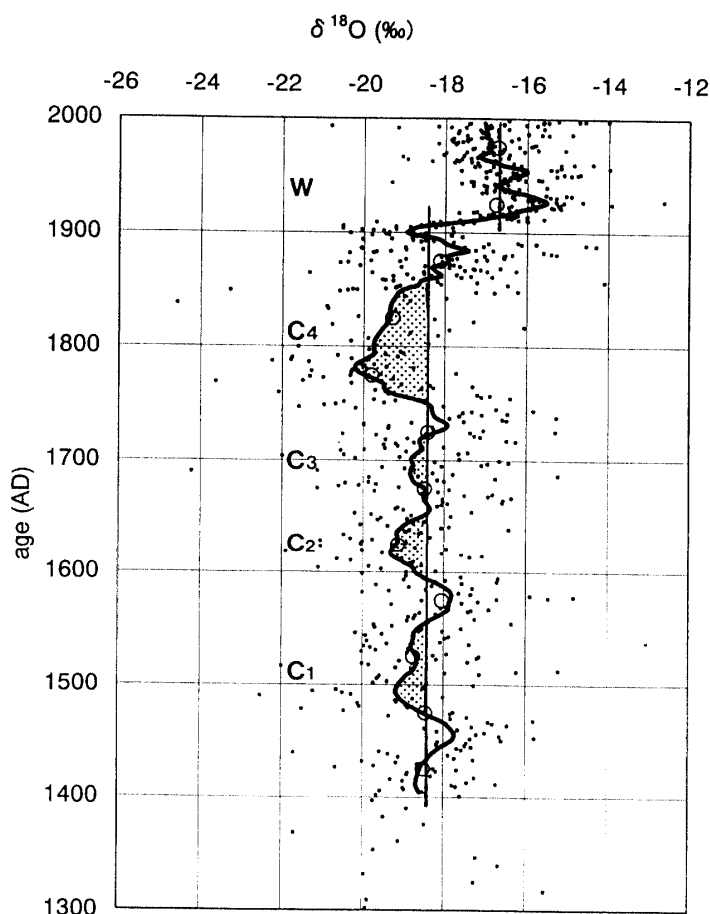


Fig. 11. Reconstruction of climatic and environmental change.

Climatic phases during the little ice age.

C (cold phase) 1: 1475–1554 AD, C2: 1596–1652, C3: 1676–1721, C4: 1752–1859, W (warm phase after little ice age): 1920–1999 AD.

The annual flux of several chemical compositions over the interval of C1–C4 cooler periods and the warmer period (W; after 1920) are shown in Fig. 12 and the numerical data in Table 4. Except for C3, the chemical fluxes of cooler periods (C1, C2 and C4) are of the same order and smaller value than those in the warmer period (W).

Since the Svalbard archipelago is located at the boundary between the multi-year sea ice pack and the seasonally ice-covered zone, the location of the multi-year sea ice limit changes from year to year. The remarkable decrease of the flux of major chemical constituents, Na^+ , Cl^- , SO_4^{2-} and NO_3^- found in C3 may relate to cryospheric conditions such as sea ice distribution. The long cooler duration, as was estimated from Fig. 11 below the average line, was possibly responsible for the small fluxes.

As shown in Fig. 13, the correlation between the firm ratio and $\delta^{18}\text{O}$ was good from 1400 to 1750 and since 1900, but from 1750 to 1900, when there was strong cooling, there was a clear inverse correlation. This is in contradiction with the general trend for melting of accumulated snow to increase in a cold period. Perhaps it is possible to infer that during the Little Ice Ages the area covered by sea ice in the Barents Sea increased, the area of open

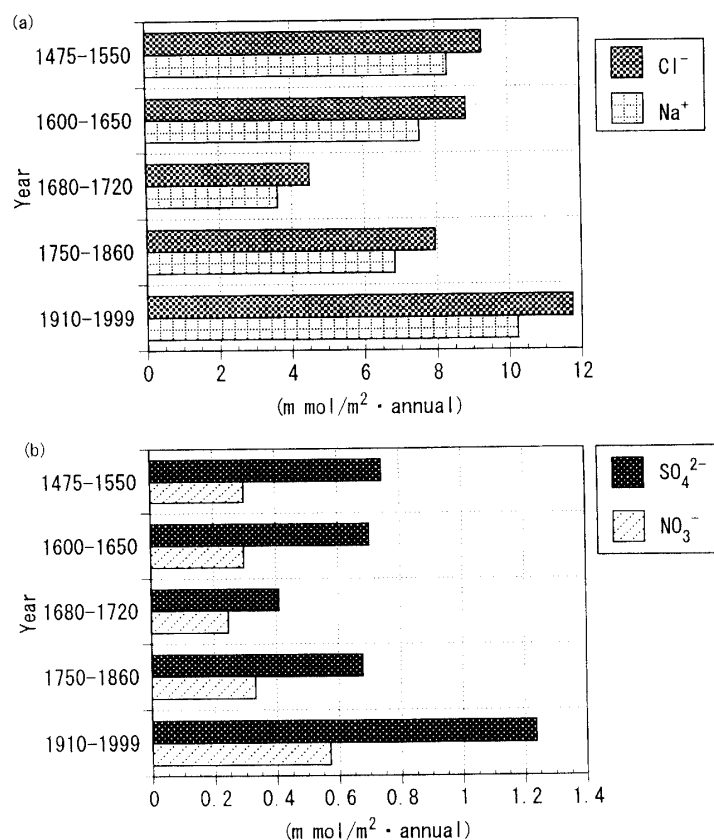


Fig. 12. Comparison of average annual chemical flux in the cold phase during the Little Ice Age.

Table 4. Average of annual chemical flux in the different climatic phase.

Depth (m)	Year	Climate phase	Acc. rate ($\text{m} \cdot \text{a}^{-1}$)	Na^+	Cl^-	NO_3^-	SO_4^{2-}
				(m mol \cdot m $^{-2}$ \cdot a $^{-1}$)			
0- 48.3	1999-1920	Warm	0.54	10.23	11.75	0.57	1.24
72.6-119.8	1860-1750	Cold 4	0.44	6.85	7.95	0.33	0.68
133.1-151.1	1720-1680	Cold 3	0.40	3.62	4.52	0.25	0.41
161.0-182.6	1650-1600	Cold 2	0.39	7.55	8.84	0.30	0.70
198.2-225.6	1550-1475	Cold 1	0.35	8.33	9.29	0.30	0.74

water in summer decreased and, particularly, that the amount of precipitation in summer decreased, so that there was the little cloud cover and little vapor transport. As seen in Table 3, compared to the period 1920-1963, the precipitation from 1783 to 1920 was lower (0.44 compared to 0.57 $\text{m} \cdot \text{water} \cdot \text{a}^{-1}$) as was the Na^+ flux (7.60 compared to 12.55 $\text{m mol} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$); perhaps these figures support the above inference.

6. Concluding remarks

By comparing the multiple ice cores from different locations on Nordaustlandet, Svalbard archipelago, reconstruction of climatic and environmental change during the last

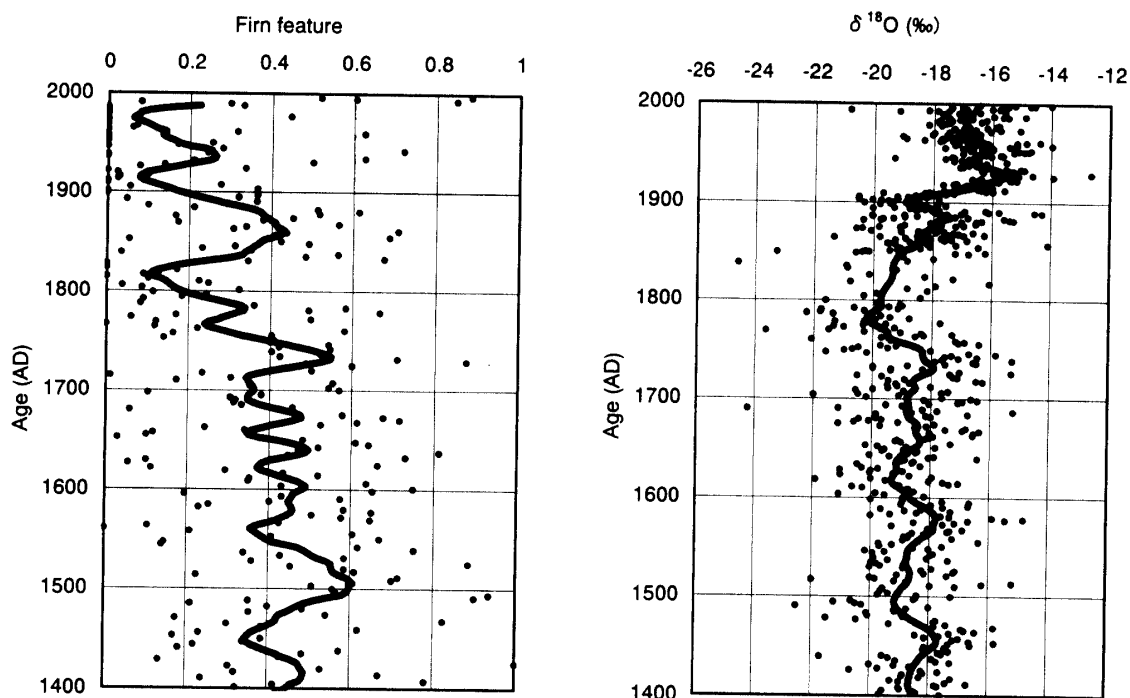


Fig. 13. Relation between firn ratio and climatic change at Austfonna.

few hundred years has been discussed.

The $\delta^{18}\text{O}$ records from Austfonna and Vestfonna ice cores correlated well with the temperature records since 1915 in Isfjord Radio. This suggests that $\delta^{18}\text{O}$ values recorded in ice cores would be important proxies for past temperatures in the Svalbard archipelago.

Ice core chemistry records can also be used to reconstruct past atmospheric conditions. Since our core analyses have not been completed yet, we need to perform preliminary analyses of the cores to obtain complete data sets. Also, we need to drill deep cores reaching the bedrock to reconstruct the Holocene climatic changes.

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